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Section

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MODIFICATION OF MATERIALS LOCAL PROPRIETIES BY FRICTION STIR PROCESSING

BY

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and DANUT IORDACHESCU***

Abstract. Friction stir processing (FSP) is a new solid state processing technique that can eliminate casting defects and refine microstructures, enhancing formability and improving other properties. FSP can also produce fine-grained microstructures through thickness. Essentially, FSP is a local thermo-mechanical metal working process that changes the local properties without influencing the properties of the bulk material. Firstly, the paper introduces FSP fundamental parameters, as advancing and rotating tool speed, approaching their influence on the processed surface roughness of Al6061. Single and overlapped friction stir processed layers were considered for the roughness analysis. Roughness mapping revealed existence of transitory and quasi-stationary phases of FSP. A process monitoring method obtaining through roughness control is envisaged. The paper also presents the material flow, microstructure and hardness in case of aluminium processed by FSP.

Key words: *FSP, material flow, microstructure, hardness, roughness.*

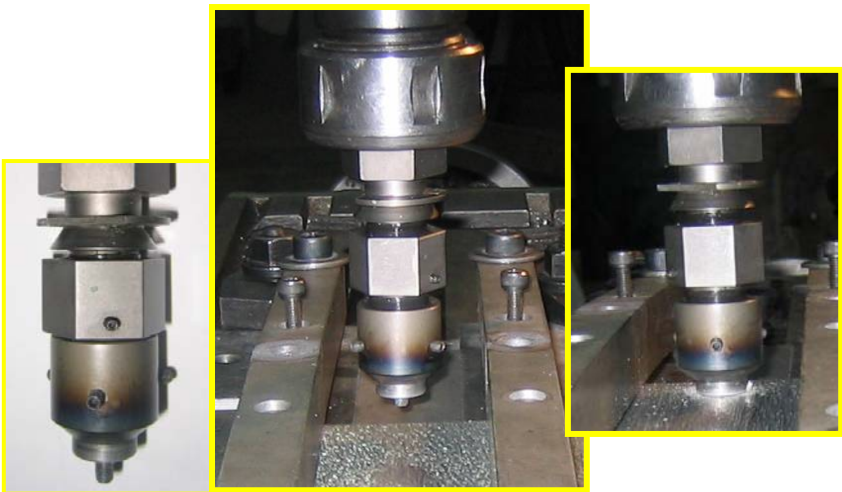
1. Introduction

Aluminum alloys are used in aircraft construction since the 1930s. The aerospace industry relies on 2xxx and 7xxx alloys, but 6xxx aluminum alloys are of particular interest nowadays. According to Troeger [1], 6xxx alloys have numerous benefits including medium strength, formability, weldability, corrosion resistance and low cost.

Presently, after appropriate heat treatments, 6xxx alloys are used in a variety of applications including aircraft fuselage skins and automobile body panels and bumpers, instead of more expensive 2xxx and 7xxx alloys. However some issues to practical application concerning the less wear resistance and inherent defects in casting exist [2]. Many attempts tried to overcome this poor resistance characteristic using fusion processes including welding, laser and plasma processes, but defects as porosity and cracks occur in the surface modified zone.

A major milestone was reached in 1991 when Thomas Wayne from The Welding Institute in UK (TWI) patented Friction Stir Welding (FSW), extending the opportunities of using frictional heat for solid state joints obtaining [3]. Since then, the metallurgists and mechanical engineers are investigating Friction Stir Processing (FSP), a derivative of FSW, as a potentially useful technique for surface modification of aluminum alloys. Moreover, FSP provides the ability to thermo-mechanically process selective locations on the structure's surface and to some considerable depth, enhancing specific properties [4].

The paper introduces FSP fundamental parameters as advancing and rotating tool speed, approaching their influence on the processed surface of as-cast AA6061. Single and overlapped friction stir processed layers were considered for the process analysis.



a b c

Fig.1 - FSP of as-cast AA6061 aluminium alloy:
a - tool desing; b - tool rotating before the contact with the plate; c - processing phase.

2. Experimental Procedure

FSP is a useful technique for surface local properties modification of aluminum alloys, designed to refine the structure of surface layer and improve its properties. To friction process a location within a plate, a specially designed cylindrical tool (Fig.1) is rotated and plunged into the selected area. The tool has a small diameter threaded pin with a concentric and larger diameter shoulder. FSP tool characteristics are presented in Table 1. When the rotating pin contacts the surface it rapidly friction heats and softens a small column of metal. The tool shoulder and the length of the entry probe control the penetration depth. When the shoulder contacts the metal surface, its rotation creates additional frictional heat and plasticizes a larger cylindrical metal column around the inserted pin. The shoulder provides a forging force that contains the upward metal flow caused by the tool pin.

During FSP, the processed area and the tool are moved relative to each other such that the tool traverses, with overlapping passes, until the entire selected area is processed.

The tool rotating provides a continuing hot working action, plasticizes the metal within a narrow zone, while the material is transported from the leading face of the pin to its trailing edge. The process is carried out at low temperature, in solid state, typically below 0.3 of the fusion temperature (Tf) for aluminium alloys. The processed zone is deformed and under the thermal effect recovers a fine grain microstructure is developed.

Table 1
FSP tool characteristics

Tool size		
Shoulder diameter, mm	Pin diameter, mm	Pin length, mm
15	5	4

The process main operating parameters are friction pressure (tool up-setting force), tool rotation and travel speed are presented in Table 2.

The modified layer thickness is directly related to the friction pressure, whereas it is inversely affected by the rotation speed of friction tool and the traverse speed. The microstructure and properties of the modified layer depend on the amount of frictional heat generated by processing.

Table 2
Processing parameters

FSP parameters			
Rotation speed, rpm	Travel speed, mm/min	Friction pressure, kN	Pin angle, ^{0}
1120	320	25	2.5

Table 3
Chemical composition of cast AA 6061 aluminium alloy

Chemical composition (WT %)							
Si	Fe	Cu	Mn	Mg	Cr	Zn	Al
0.66	0.25	0.31	0.08	0.99	0.16	0.01	balance

The research was conducted on as-cast AA6051 aluminium alloy plates, simulating the flat-shaped ingots, of 10 mm thickness. Their chemical composition is presented in Table 3. The samples 300 X 200 X 10 mm were longitudinally friction stir processed. As Fig. 2 presents, FSP single and overlapped layers were made.

Samples of different layers cross-sections were prepared by using standard metallographic procedures. A modified Keller's reagent was used for their etching. Observations of plastic deformation, material flow and microstructures were performed by using optical microscopy. Vickers microhardness measurements were performed on processed layers cross-sections by using a microhardness tester at a 100 g load and a 15 s dwell time. Moreover, the roughness analysis was performed on processed surface.

Fig.2 - FSP single and overlapped layers.

3. Results and Discussion

3.1. *Material Flow and Microstructure*

From the macrographs, shown in Fig. 3, both the thermomechanically affected zone (TMAZ), which consists of the weld nugget and plastically deformed grains, and part of the heat affected zone (HAZ) are evident. The concentric rings seen within the nugget are also visible, as is the appendage to the nugget that stretches to the surface.

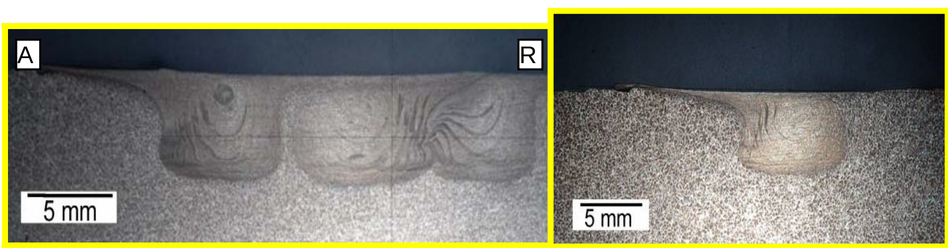


Fig.3 - Macrostructures of FSP single and overlapped layers
A – advancing side; R – retreating side.

The base metal (BM) microstructure of as-cast AA 6061 (Fig. 4) consists of Al solid solution dendrites along with coarse silicon and intermetallic phases. Shrinkage porosity is also prevalent.

According to Fig. 4, FSP closed the shrinkage porosity and homogenized the as-cast microstructures by breaking up and evenly dispersing initial phases.

Fig. 4 shows the typical features of all different zones in a single processed layer cross-section of as-cast AA 6061 under processing condition of 1120 rpm for the rotational speed and 320 mm/min for the welding speed. The positions 1-6 from Fig. 4 are located in different microstructural zones.

The micrographs show that the microstructure of the processed layer is complex and highly dependent on the position within the processed zone. This result arises because of the large local variations in the plastic flow and from the thermal history resulted from the material interaction with the tool.

The characteristic annular-banded structure is distinctly observed to be asymmetric and more obvious on the advancing side (A) of processed zone as shown in Fig.4, positions 1, 2, 4. A severe deformation has also occurred along the top surface of the processed layer where the shoulder of the tool is in contact with the material.

The flow lines from Fig. 4, positions 4, 2, 5 seams to represent plastic deformation increments that develop as the rotating tool moves through the processing line.

Although it is well known that the material is transported from the advancing side to the retreating side (R), Colligan [2] showed that with a threaded pin tool the material from the upper part of the processed zone is pressed down, whereas the material from the lower part processed zone is moved toward the top surface.

The material may travel many cycles around the tool before being redeposited. A little flow of material was observed near the bottom of the processed zone.

The microstructure in the stir zone is characterized by refined grains in a discrete series of bands and some precipitate mainly distributed at the grain boundaries (Fig. 4). There is also still some debate concerning the origin of the annular rings observed within the nugget zone attributed to an abrupt variation in the grain size and precipitate density [6].

The nugget zone grains suggest effective strains together with a microstructural evolution that occurs by a combination of hot working and a dynamic recovery or recrystallization. The temperature reached in the nugget zone is known to be in the range of 450-500ºC for the 6061- Al alloy [7]. Distinct precipitates and coarsened grains are observed at the deformed regions of TMAZ. HAZ grains are severely coarsened by FSP (Fig. 4, positions 1, 4).

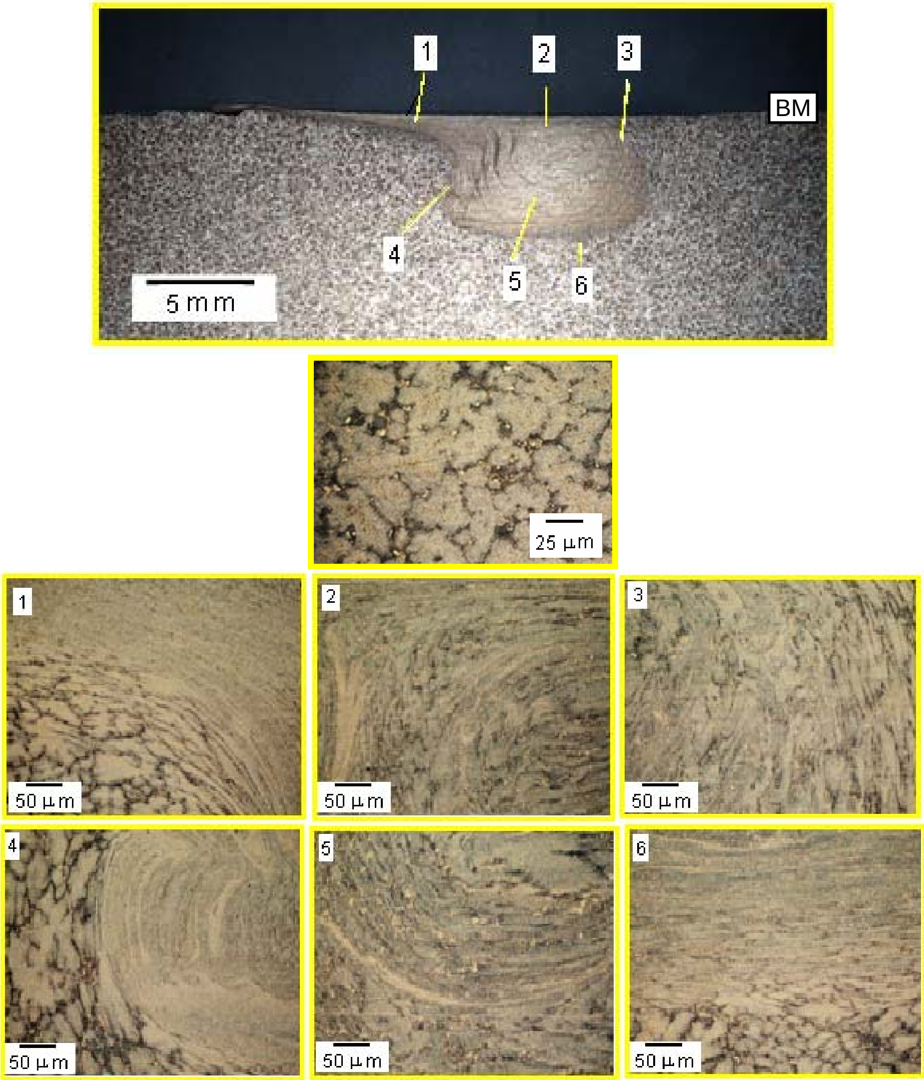


Fig.4 - Typical features of all different zones in a friction stir processed single layer cross-section of as-cast AA6061: BM - base metal pancake microstructure; 1- flow patterns in the appendage zone; 2 – nugget zone; 3 – the retreating side of TMAZ; 4 – the advancing side of TMAZ; 5 – nugget bottom side; 6 – processed layer bottom side.

3.2. *Hardness Distribution in the Processed Material*

Fig. 5 shows the typical microhardness distribution of the single layer processed cross-section of as-cast AA 6061 alloy. The base metal minimum hardness value was of 68 HV0.1. Generally, there is an increase of hardness in the processed layer. A significant variation in hardness is found at 2.5 mm depth from the processed surface. A maximum value of 85 HV0.1 was registered at this depth, which corresponds to the interface nugget - thermomechanically affected zone. Although on the top surface of the processed layer maximum temperatures occur, the hardness increases up to 78 HV0.1.

The hardness increasing of as-cast AA 6061 alloy by friction stir processing depends on the process parameters, tool rotating and advancing speed, influencing the degree of grains refinement and level of uniformity in distribution of precipitation hardening phase, Mg_2Si.

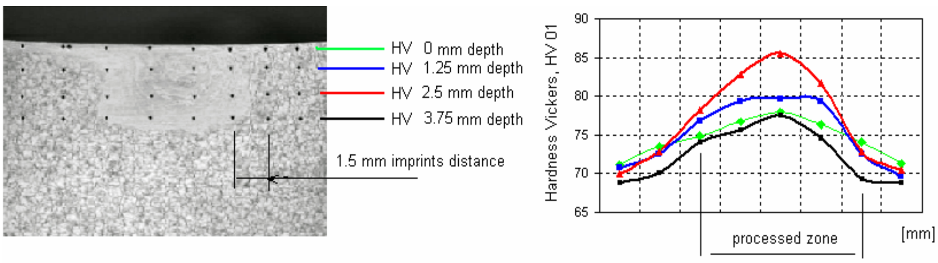


Fig.5 - Typical microhardness distribution in a friction stir processed single layer cross-section of as-cast AA6061.

3.3. *Processed Material Roughness*

Fig. 6 shows typical roughness distribution of the single layer processed cross-section of as-cast AA 6061 alloy. The analysis was made on A, B and C lines of 4 mm length (Fig. 6).

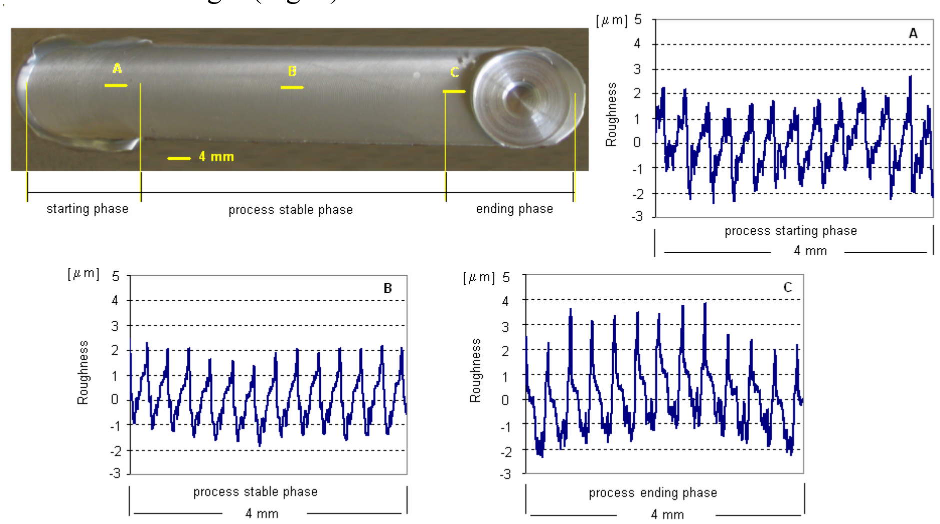


Fig.6 - Roughness distribution on a friction stir processed single layer of as-cast AA 6061.

The roughness profiles revealed the existence of transitory and quasi-stationary phases of FSP. The transitory phases correspond to the starting and the ending moments of the process, due to the material increased heating. Maximum profile heights of 3.68 μm were registered on the surface of the process ending phase. In the quasi-stationary phase, namely the process stable phase, maximum profile height of 2.2 μm was found out. A process monitoring method obtaining through roughness control can be developed.

4. Conclusions

Several conclusions can be underlined about FSP of as-cast AA 6061:

1. the process makes an effective surface modification; FSP closed the shrinkage porosity and homogenized the as-cast microstructures by breaking up and evenly dispersing initial phases.
2. the material plastic deformation, flow and mechanical mixing exhibit distinctly asymmetric characteristics at advancing, retreating side zones.
3. the hardness increasing of as-cast AA 6061 alloy by friction stir processing depends on the process parameters, tool rotating and advancing speed, influencing the degree of grains refinement and level of uniformity in distribution of precipitation hardening phase, Mg_2Si.
4. a global increased hardness was found out in the processed layer. A significant variation in hardness is found at 2.5 mm depth from the processed surface. A maximum value of 85 HV0.1 was registered at this depth.
5. the roughness profiles revealed the existence of transitory and quasi-stationary phases of FSP. The transitory phases correspond to the starting and the ending moments of the process, due to the material increasing, respectively decreasing heating.
6. the process may address to the industry as a surface repairing technique for different types of flaws and surface hardening.

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MODIFICAREA PROPRIETĂȚILOR LOCALE ALE MATERIALELOR PRIN PROCEDEUL FSP

(Rezumat)

În anul 1991 Thomas Wayne de la Institutul de Sudare din UK (TWI) a patentat procedeul de sudare prin frecare cu element activ rotitor, FSW, extinzând metoda utilizării căldurii prin frecare în domeniul obținerii unor îmbinări în stare solidă. Cercetătorii din domeniile metalurgiei şi mecanicii investighează procedeul de prelucrare cu element activ rotitor (FSP), un procedeu derivat din FSW, în ideea modificării, prin această tehnică, a proprietăților de suprafață a aliajelor de aluminiu.

Procesarea prin frecare cu element activ rotitor (FSP) este o tehnică nouă de procesare a materialelor în stare solidă, cu ajutorul căreia se elimină defectele de turnare, se finisează granulația şi se îmbunătățesc o serie de proprietăți tehnice cum ar fi deformabilitatea. Prin acest procedeu este posibilă finisarea grăunților cristalini pe grosimea materialelor. Procesarea prin

frecare cu element activ rotitor este un proces termo-mecanic local prin care se pot modifica proprietățile locale, fără a afecta întregul material.

În lucrare sunt prezentați principalii parametri care caracterizează procesul FSP, cum ar fi vitezele de avans şi de rotație ale dispozitivului de procesare, şi influența lor asupra rugozității suprafeței procesate, pentru cazul aliajului de aluminiu Al6061.

Pentru a studia variația rugozității suprafeței prelucrate, s-au analizat probe procesate dintr-o singura trecere şi probe procesate din mai multe treceri. Valorile rugozității au relevat faptul ca procesul FSP este caracterizat prin existența fazelor tranzitorii şi cvasistaționare. În lucrare sunt prezentate şi cercetări privind curgerea materialului, microstructuri ale suprafeței prelucrate şi variația durității în cazul procesării aluminiului prin procedeul FSP.